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Production of J/ψ-pairs at HERA-$\vec{\mathrm{N}}$

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Abstract

The production of J/ψ-pairs as a possible measure of the polarized gluon distribution $\Delta G(x)$ is studied for proton–nucleon collisions at $\sqrt{s} = 40$ GeV^2 (HERA-$\vec{\mathrm{N}}$). Possibilities of reconstructing the helicity state of at least one of the J/ψ's are critically reviewed. The observation of production asymmetries in the single polarized mode of HERA-$\vec{\mathrm{N}}$ is found to be not feasible.

1 Introduction

So far, all experimental measurements of the spin structure of the nucleon are measurements of the polarized structure function $g_1(x, Q^2)$ [1]. At leading order, this structure function reflects the polarization of quarks in the nucleon

$$g_1(x, Q^2) = \frac{1}{2} \sum_q e_q^2 \left(q_\uparrow(x, Q^2) - q_\downarrow(x, Q^2) \right), \tag{1}$$

while contributions from the polarization of gluons in the nucleon only enter via higher order corrections to the above expression. The data obtained from these experiments determine the polarization of valence quarks in the nucleon with an uncertainty of about $\pm 25\%$. The polarization of gluons in the nucleon, parametrized by

$$\Delta G(x, Q^2) = G_\uparrow(x, Q^2) - G_\downarrow(x, Q^2) \tag{2}$$

can hardly be deduced from the g_1 measurements, although some estimates exist[2, 3, 4]. In the recent past, various experimental groups have proposed direct measurements of $\Delta G(x, Q^2)$ from open charm production in polarized lepton-nucleon scattering [5], photoproduction of J/ψ mesons [6] and asymmetry measurements in polarized hadron-hadron collisions [7]. At this time, only one of these experiments is approved [7] and scheduled for data taking in the year 2000.

The HERA-$\vec{\mathrm{N}}$ experiment[8] would provide an earlier opportunity of singly polarized (unpolarized beam on polarized target) hadron–hadron collisions. This experiment would use the (modified) HERMES target and spectrometer [9] in the HERA proton beam, and hence the maximal centre-of-mass energy would be

$$\sqrt{s} = 40 \text{ GeV}. \tag{3}$$

Amongst various possibilities for the integrated luminosity, only the so–called high–luminosity option

$$\int \mathcal{L} \mathrm{d}t = 240 \text{ pb}^{-1} \tag{4}$$

will provide sufficient statistics for rare channels such as the one under consideration in this paper.

In this paper, we will examine the possibility of determining $\Delta G(x, Q^2)$ at HERA-$\vec{\mathrm{N}}$ from a measurement of production asymmetries of J/ψ pairs. In the following section, we briefly outline the predictions of the colour singlet model for the production of J/ψ pairs. Section 3 examines possible ways of reconstructing J/ψ mesons and their helicity state at HERA-$\vec{\mathrm{N}}$. In section 4, we compare the production asymmetries in this channel for various, equally possible parametrizations of $\Delta G(x, Q^2)$. Finally, section 5 contains our conclusions.

2 Production of J/ψ pairs in the colour singlet model

The nonrelativistic colour singlet model [10] describes the production of J/ψ mesons as arising from the production of a charm quark pair. Both quarks forming the J/ψ have exactly half its velocity and form a colour singlet. The transition amplitude from the quark pair to the meson state is then inferred from the magnitude of the J/ψ wavefunction at the origin. This model sucessfully describes the production of J/ψ mesons in lepton-hadron collisions [11], provided the theory prediction is scaled with a K-factor accounting for higher order corrections. This K-factor is of order 4 and almost independent of the kinematical variables. The next-to-leading order calculation of J/ψ photoproduction [12] is in better agreement with the experimental data, but still needs to be scaled by a (smaller) K-factor.

This model can be generalized to the production of J/ψ pairs in hadron-hadron collisions, yielding the parton level cross section

$$\frac{\mathrm{d}\hat{\sigma}(a + b \to J/\psi J/\psi)}{\mathrm{d}\cos\Theta^\star} = \frac{\pi^3 \alpha_s^4 (1 - M_{J/\psi}^2/\hat{s})^{1/2}}{72\hat{s}} \frac{|\Psi(0)|^4}{M_{J/\psi}^2} \frac{1}{64} |\mathcal{M}|^2 \qquad (a+b = q+\bar{q} \text{ or } g+g).$$

$$(5)$$

The helicity averaged matrix element $\mathcal{M}$ was first calculated in [13], and its full helicity dependence was derived in [14][1].

To relate this parton level cross section to a measurable observable at the hadronic level, it has to be convoluted with the corresponding parton distributions

$$\mathrm{d}\sigma(p + p \to J/\psi J/\psi) = \sum_{a,b} \int \mathrm{d}x_1 \mathrm{d}x_2 f_{a/p}(x_1) f_{b/p}(x_2) \mathrm{d}\hat{\sigma}(a + b \to J/\psi J/\psi). \qquad (6)$$

The above expression is dominated by the $(g+g)$ subprocess, whose contribution is about five times as big as the one from $(q + \bar{q})$ at HERA-$\vec{\mathrm{N}}$ energies. In all further studies, we will restrict us to the gluonic contribution.

To estimate the expected cross section at $\sqrt{s} = 40$ GeV, we have evaluated the above expression for the leading order parton distributions given in [15] (DO1.1) and [16] (GRV94). The resulting p_T^2 distributions are shown in Figure 1. We use $\Lambda_{QCD}^{(4)} = 200$ MeV and $|\Psi(0)|^2 = 0.043$ GeV^3, obtained from the leptonic width of the J/ψ [17].

The large discrepancy between both predictions reflects mainly the uncertainty on the unpolarized gluon distribution $G(x)$ in the high-x region. For consistency with the polarized distributions considered in the remainder of this paper, we will work with $G(x)$ from GRV94 [16]. For the proposed high-luminosity option of HERA-$\vec{\mathrm{N}}$, one can expect 1200 J/ψ pairs to be produced.

It should be kept in mind that the colour singlet model assumes the colour neutrality of the $(c\bar{c})$-pair to be obtained by a single, hard gluon emision. This condition is only satisfied for sufficiently large transverse momentum of the final state particles. In the

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[1] We would like to thank Sergey Baranov for providing the FORTRAN-code for $\mathcal{M}$

	σ^{tot}	$\sigma(p_T^2 > 1 \text{ GeV}^2)$
DO1.1	10.3 pb	6.5 pb
GRV94	4.9 pb	3.0 pb

Table 1: Total cross sections for $pp \to J/\psi J/\psi$ evaluated for the parton distributions of [15] and [16].
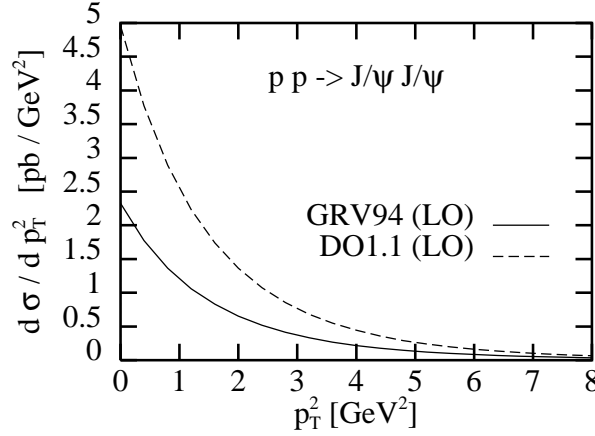

Figure 1: Cross section for production of J/ψ pairs at HERA-$\vec{\text{N}}$

forward region ($p_T^2 \lesssim 0.5 \text{ GeV}^2$), the same neutral state can be obtained by the multiple emission of soft gluons. Hence the colour singlet model tends to underestimate the cross section in this region.

3 Reconstruction of the J/ψ

The total cross section for proton-proton collisions at $\sqrt{s} = 40$ GeV is $\sigma^{tot}(pp) = 41$ mb [17], ten orders of magnitude bigger than the cross section for the production of J/ψ pairs. In order to identify these events in the background of mulithadron production, a clear decay signature of at least one of the J/ψ mesons is needed. Only the leptonic decay $J/\psi \to \gamma^* \to l^+l^-$ can provide such a clear signature, as the pair of oppositely charged leptons can be easily distinguished from the hadronic background. The branching ratio [17]

$$Br(J/\psi \to \gamma^* \to l^+l^-) = 12\% \tag{7}$$

of this decay channel therefore reduces the number of visible events.

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HERA-$\vec{\mathrm{N}}$ will (at least for the first years of running) only have a polarized target, with an unpolarized beam. Information on the initial state polarization will therefore have to be extracted from the final state. In the case of J/ψ pair production, at least the helicity of one of the J/ψ's has to be measured. As the J/ψ is a massive spin-1 vector meson, it has three possible helicity states: $-1, 0, +1$. The 0 and ± 1 states correspond to different partial waves, and can therefore be easily distinguished from the energy spectra of the decay products. Unfortunately, no information on the initial state polarization can be gained from the 0 state, as the corresponding differential cross section is symmetric under the change of one initial state helicity. We will discuss the possible decay channels of the J/ψ with a view to distinguishing the $+1$ and -1 helicity states:

(i) **weak decays:** Parity violating weak decay modes could provide a clear separation between these two states. As the J/ψ does not have any known weak decay modes, this possibility is ruled out.

(ii) **leptonic decays:** Parity invariance of the electromagnetic interaction relates the decay cross sections of both helicity states. As the lepton helicities cannot be measured, both states are indistinguishable.

(iii) **decays to scalar mesons:** The distribution of the final state particles in these decays is given by the $l = 1, m = \pm 1$ partial waves. As the partial waves for $m = -1$ and $m = 1$ are identical for vector particles, this decay channel cannot distinguish between these states.

(iv) **radiative decays:** If the J/ψ decays into a real photon and scalar mesons (e.g. $J/\psi \rightarrow \eta_c \gamma$), the helicity of the J/ψ could be reconstructed from the measured helicity of the photon[2]. This decay channel contributes with a branching ratio of about 4%[17]. Provided a helicity measurement on the photon, this is the only channel in which the helicity of the J/ψ can be measured.

From the above considerations, it becomes clear that a J/ψ pair produced in single polarized proton-proton collisions can only be used for an asymmetry measurement for the specific final state configuration in which one J/ψ decays leptonically while the other decays into a photon accompanied by scalar mesons. The probability of this configuration is

$$P = 2 \times \Big(Br(J/\psi \rightarrow l^+ l^-) \Big) \times \big(Br(J/\psi \rightarrow \gamma + \mathrm{scalars}) \big) \simeq 1\%. \qquad (8)$$

Therefore, only twelve of the expected 1200 events can provide an asymmetry measurement under ideal experimental conditions at HERA-$\vec{\mathrm{N}}$. It should therefore be already clear at this point that such a measurement will fail to provide information on $\Delta G(x)$. Regardless of this negative result, we will provide an estimate of the asymmetries one could expect at HERA-$\vec{\mathrm{N}}$.

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[2]Even though such a measurement could be possible in principle, it seems rather doubtful that it could be carried out with the HERA-$\vec{\mathrm{N}}$ apparatus.

4 Asymmetries at HERA-$\vec{\text{N}}$

Under ideal experimental conditions at HERA-$\vec{\text{N}}$, the spin of the target proton and the helicity of one of the two J/ψ mesons can be measured in a rather small fraction of the events. Using this information, we can construct the following asymmetry

$$A = \frac{\mathrm{d}\sigma(p^+ J/\psi^+) + \mathrm{d}\sigma(p^- J/\psi^-) - \mathrm{d}\sigma(p^- J/\psi^+) - \mathrm{d}\sigma(p^+ J/\psi^-)}{\mathrm{d}\sigma(p^+ J/\psi^\pm) + \mathrm{d}\sigma(p^- J/\psi^\pm)}. \tag{9}$$

This asymmetry can be related to the parton level cross sections, keeping in mind that the helicity state of the second J/ψ is summed over. For convenience, we use the following shorthand notation for the parton level matrix elements of particular helicity combinations:

$$[h(g, \text{beam})\, h(g, \text{target})\, h(J/\psi_1)\, h(J/\psi_2)] \equiv$$
$$\mathrm{d}\hat{\sigma}(g(h(\text{beam})) + g(h(\text{target})) \to J/\psi(h_1) J/\psi(h_2)). \tag{10}$$

Omitting terms related by parity invariance, the asymmetry is

$$A = \frac{\int \mathrm{d}x_1 \mathrm{d}x_2 G(x_1, Q^2) \Delta G(x_2, Q^2) \left\{ 2[\Sigma\Delta + +] + [\Sigma\Delta 0 +] + [\Sigma\Delta + 0] \right\}}{\int \mathrm{d}x_1 \mathrm{d}x_2 G(x_1, Q^2) G(x_2, Q^2) [\Sigma\Sigma \pm \pm]}, \tag{11}$$

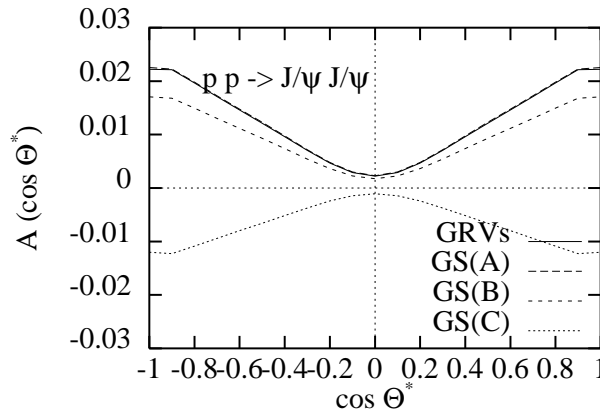where Σ (Δ) denotes the sum (difference) of the possible helicity states.

Figure 2: Expected asymmerty in the single polarized mode of HERA-$\vec{\text{N}}$.

The scale of the parton distributions in the above expression and the scale of $\alpha_s(Q^2)$ in the matrix elements is taken to be $Q^2 = (M_{J/\psi})^2$. We have evaluated the above asymmetry as a function of the angle between the J/ψ pair and the proton beam direction in the parton-parton centre-of-mass system (which can be reconstructed from the final state).

The unpolarized $G(x, Q^2)$ is taken from [16]. In Figure 2, we compare the predictions obtained with the parametrizations of $\Delta G(x, Q^2)$ from [3] (standard scenario) and [4] (Gluon A-C). Althogh the asymmetries obtained with these parametrizations are significantly different from each other, $A(\cos \Theta^\star)$ never exceeds 3%. The asymmetry becomes maximal if the J/ψ pair is produced at very small angles with respect to the proton beam, i.e. at low transverse momenta.

Keeping in mind the low number of reconstructable events, this small asymmetry turns out to be unmeasurable in the single polarized mode of HERA-$\vec{\text{N}}$. The situation would be different for a double polarized measurement (i.e. with a polarized HERA proton beam): in this case, the reconstruction of helicities in the final state is no longer necessary for an asymmetry measurement. Therefore, one can expect about 270 J/ψ pairs with at least one lepton pair decay. The asymmetry can be defined in the standard way

$$A = \frac{\mathrm{d}\sigma(p^+ p^+) + \mathrm{d}\sigma(p^- p^-) - \mathrm{d}\sigma(p^+ p^-) - \mathrm{d}\sigma(p^- p^+)}{\mathrm{d}\sigma(pp)}. \tag{12}$$

In terms of the parton densities this asymmetry reads

$$A = \frac{\int \mathrm{d}x_1 \mathrm{d}x_2 \Delta G(x_1, Q^2) \Delta G(x_2, Q^2)[+\Delta \Sigma \Sigma] - [-\Delta \Sigma \Sigma]}{\int \mathrm{d}x_1 \mathrm{d}x_2 G(x_1, Q^2) G(x_2, Q^2)[\Sigma \Sigma \Sigma \Sigma]} \tag{13}$$
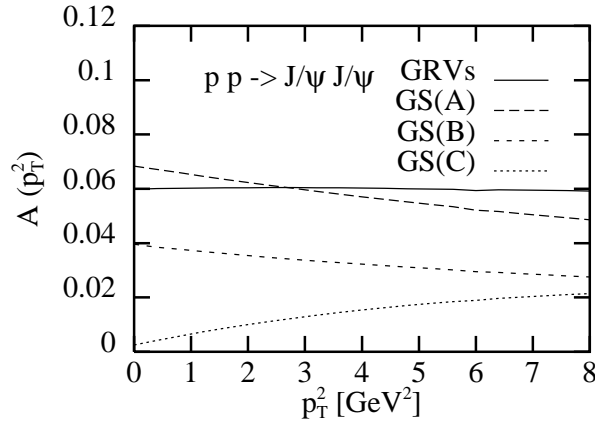

Figure 3: Expected asymmetry in the double polarized mode of HERA-$\vec{\text{N}}$.

Figure 3 shows this asymmetry as a function of p_T^2 for the parametrizations of $\Delta G(x, Q^2)$ mentioned above. Depending on the parametrization, the asymmetry could be as large as 7% and only weakly depends on p_T^2. If HERA-$\vec{\text{N}}$ would have a polarized HERA proton beam available, this measurement could give some indications on $\Delta G(x, Q^2)$ for $x \approx 0.3$.

5 Conclusions

In this paper, we have studied the measurability of $\Delta G(x, Q^2)$ from the production of J/ψ pairs at HERA-$\vec{\mathrm{N}}$. We showed that a measurement in the single polarized mode is not feasible due to the low cross section and the problematic reconstruction of the helicity state of the J/ψ. At best, one could reconstruct twelve events in this channel, which is insufficient to determine an asymmetry of at most 3%. The situation improves in the double polarized mode. In this mode, the production of J/ψ pairs could provide (amongst other channels) a competitive measurement of $\Delta G(x, Q^2)$.

Acknowledgements

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